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GIC observations and studies in the Hydro-Québec power system

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Abstract

On March 13, 1989, at 7 h 45 UT, Hydro-Québec experienced a complete black-out of its system due to a severe geomagnetic storm. Consequently, service was interrupted for many hours and overvoltages resulting from line openings cost 6.5 M$ in material damages alone among a total of 13.2 M$. In 1991, geomagnetically induced currents (GIC) produced some effects and damages on the Radisson–Sandy Pond HVDC link. On March 24, at 21 h 55 UT, GIC larger than 110 A were measured in one of two transformers in parallel (presumably, giving a total of 220 A) at Radisson substation which led to the loss of the HVDC link. The same thing happened on October 28, but this time with material damages to equipment. From these events, short-term studies led to the upgrading of operational processes, modifications of opening thresholds of Static Var Compensators and modifications of some filters at Radisson. Also an agreement was concluded with Geological Survey of Canada (GSC) for sending a warning alert to the Network Control Centre (CCR) before any anticipated severe geomagnetic storms. Among more long-term studies, in collaboration with GSC, we have installed 5 acquisition substations along a 250-km long copper telephone line in Abitibi, a site typical of Hydro-Québec facilities, and from 1992 to 1994 measured ground voltages and magnetic fields every 10 s. The highest ground voltage measured at Louvicourt substation was ~1.70 V/km for 20 s. Asymmetry measurement of line voltages, based on techniques developed at IREQ in the 1980s, have been upgraded, the number of installations has been increased (from 4 to 8) and functions like harmonic measurement have been added. Voltage asymmetries over a fixed threshold produce an alarm at the CCR, which reacts by taking security measures in network operation. During March 1989 and 1991 events, voltage asymmetry grew to 9.6% and 15.5%, respectively, at the Arnaud substation. A major change, for needs of network stability during short circuit or other contingencies, has been the installation of series compensation in 1996 into the Hydro-Québec 735-kV network. Since capacitors block DC current, the observed asymmetry has remained about 20% of that observed before. So, now, we are confident that our network would survive the anticipated worst case GIC.
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Keywords: Geomagnetically induced current; GIC; GIC measurement; Effects of GIC on power systems

1. March 13, 1989 power failure

Between March 6 and 12, 1989, a series of enormous explosions with coronal mass ejection occurred in the same solar zone. The explosion that came at the end of the day on March 10 ejected a flow of particles (electrons, protons, and alpha) towards the earth, which reached some 50 h later. This triggered a violent geomagnetic storm which affected human installations over a period of about 30 h, i.e. from ~2 h UT on March 13 until ~9 h UT the next day (Fig. 1).

During the evening of March 12 Eastern Standard Time (EST), which is universal time minus 5 h, Hydro-Québec power system operators began to notice instabilities in the system, which they had time to correct by applying the appropriate switching operations to ensure voltage control.

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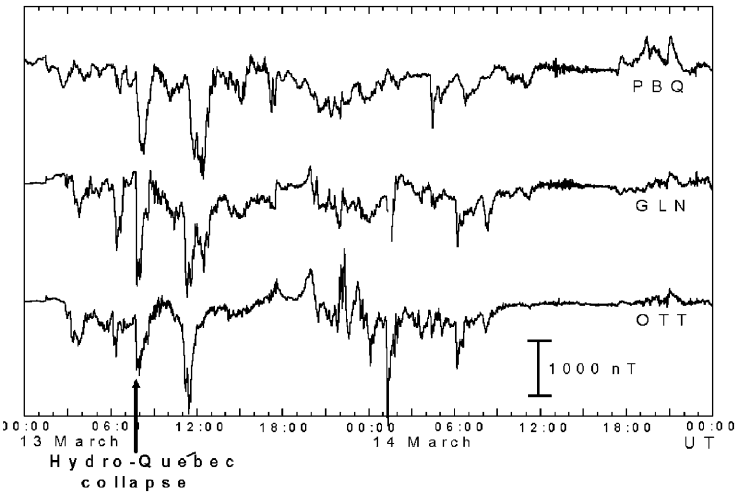


Fig. 1. Variations in earth's geomagnetic field B_x during storm on March 13–14, 1989 (Courtesy of GSC).

However, at 2:44 (7:44 UT) on March 13, just as a sudden large variation occurred in the earth's magnetic field, a number of static compensators, i.e. system components essential for maintaining dynamic stability, started tripping one after the other because of either an overcurrent or an overvoltage. The system became totally unstable: all the lines coming in from James Bay (La Grande) (Fig. 2) tripped as soon as a virtual zero appeared, with the result that the main load points were cut off from a major source of generation. The 40% load-shedding system functioned properly but it was not enough to restore the required balance between generation and consumption. In the seconds that followed, the entire system collapsed. The sequence of events is illustrated in Table 1. Fig. 3 shows how the system frequency behaved at the time of the power failure. Some 9 h later, 83% of the load had been successfully restored.

After system separation, overvoltages (similar to those observed during the system-wide failure of April 18, 1988 which was not due to a geomagnetic storm) occurred in the James Bay system and damaged equipment. The overvoltages noted on the lines arriving at Jacques–Cartier substation (James Bay side) after separation can be seen in Fig. 4. A report dated June 8, 1989 estimated that the damage to equipment amounted to $6.5 million (Table 2) and the net cost of the failure to $13.2 million (Hydro-Québec, 1989; Czech et al., 1992; Blais and Metsa, 1993; Bolduc and Langlois, 1995). Some items of transmission system equipment went back into service only months later because of the extent of the repairs involved.

The very same day, i.e. March 13, 1989, at 16:51:26.684 EST, compensator CLC-102 at Châteauguay substation tripped as a result of an overcurrent (excess harmonic current in the capacitor branch) caused by the geomagnetic storm.

Table 1
Sequence of events: Hydro-Québec blackout March 13, 1989. EST (UT - 5)

2:44:17	Tripping of compensator CLC 12 at Chibougamau
2:44:19	Tripping of compensator CLC 11 at Chibougamau
2:44:33-2:44:46	Shutdown of four static compensators at Albanel and Némiskau
2:45:16	Tripping of compensator CLC 2 at La Vérendrye
2:45:24.682	Tripping of line 7025 at Jacques-Cartier
2:45:24.936	Tripping of line 7044 at La Vérendrye
2:45:24.948	Tripping of line 7016 at La Vérendrye
2:45:24.951	Tripping of line 7026 at Chamouchouane
2:45:24.996	Fault on La Grande 4 transformer T1, Phase C
2:45:25.003	Fault on La Grande 4 transformer T3, Phase A
2:45:25.042	Tripping of line 7045 at Grand-Brûlé and La Vérendrye
This completed the separation of the La Grande network from Hydro-Québec's main transmission network. In the following 6 s the whole grid collapsed, including the shut down of Gentilly 2 nuclear substation and HVDC interconnections (two radial generation links were left in service)	
2:45:25.057	Abnormal thyristor firing due to overvoltage in stopped compensator CLC 11 at Albanel

2. Subsequent corrective measures

In the days or weeks that followed the failure, several corrective measures were applied to the equipment and to the way the system was operated. The first was the signing of an agreement with the Geomagnetic Laboratory of the Geological Survey of Canada (GSC) regarding the emission of major magnetic storm warnings 24 h a day, 7 days

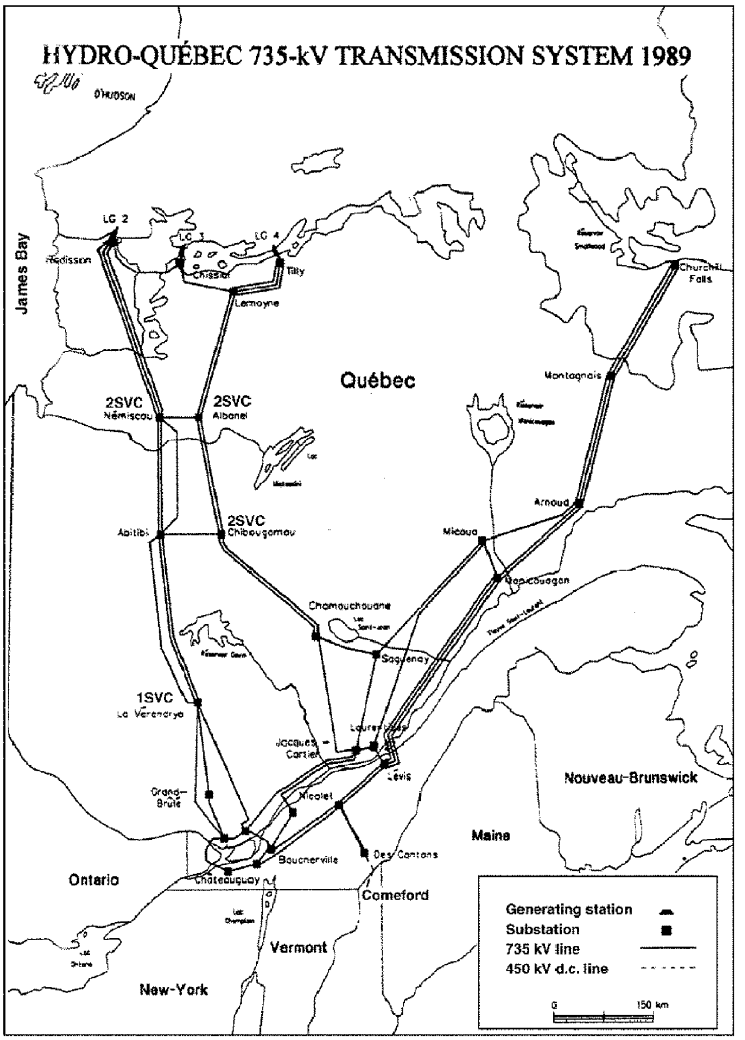


Fig. 2. Seven Static Var Compensators were operating at the time of the March 1989 event: two at Nemiskau, two at Albanel, two at Chibougamau and one at La Vérendrye.

a week, to allow system operators to take the appropriate steps in good time and follow the new system operating directives in the event of geomagnetic storms. In addition, the four-point voltage asymmetry measuring system, which was only producing information, was adapted so that it would also trigger an alarm when certain asymmetry limits were reached or exceeded. Over the years, this system has been extended to eight points while four more points have been added to measure even harmonics (Béland, 1998; Théorêt, 1995). Thus, in the event of a major magnetic storm warning or an asymmetry alarm, the operators were to ensure the system was in a safer condition by taking the following precautions:

- spreading the generation more evenly;
- increasing the spinning reserve;
- putting back in service as many lines in the system as possible;
- reducing transmission on the lines to about 80–90% of their rated capacity;
- suspending any tests under way on the system;
- reducing the number of switching operations on the system to a minimum to avoid causing instability; and
- modifying, or remotely modifying, the static-compensator tripping signals to alarm mode only, thereby forcing the compensators to remain in service.

Static compensators, which had been the weak link during the storm, were subjected to a review and it was discovered that most of them had been overprotected compared to their real capacity. It was therefore possible to raise their overvoltage or overcurrent tripping thresholds

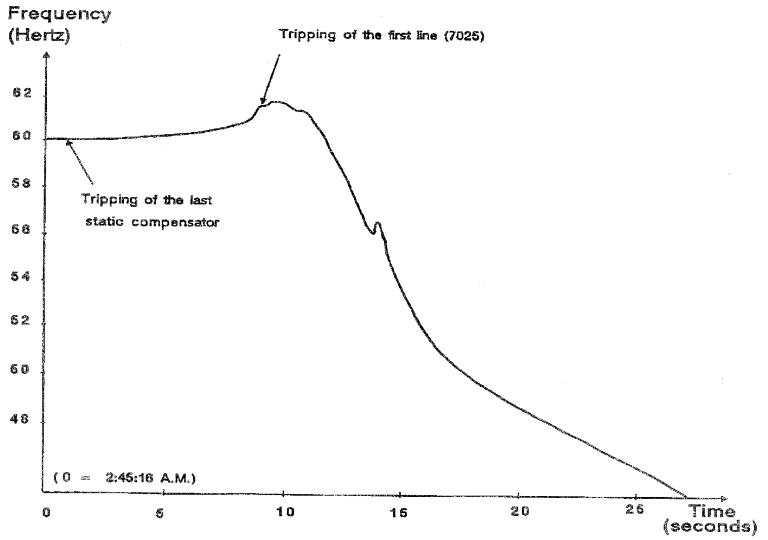


Fig. 3. Frequency at Boucherville substation at 2:45:16 EST.

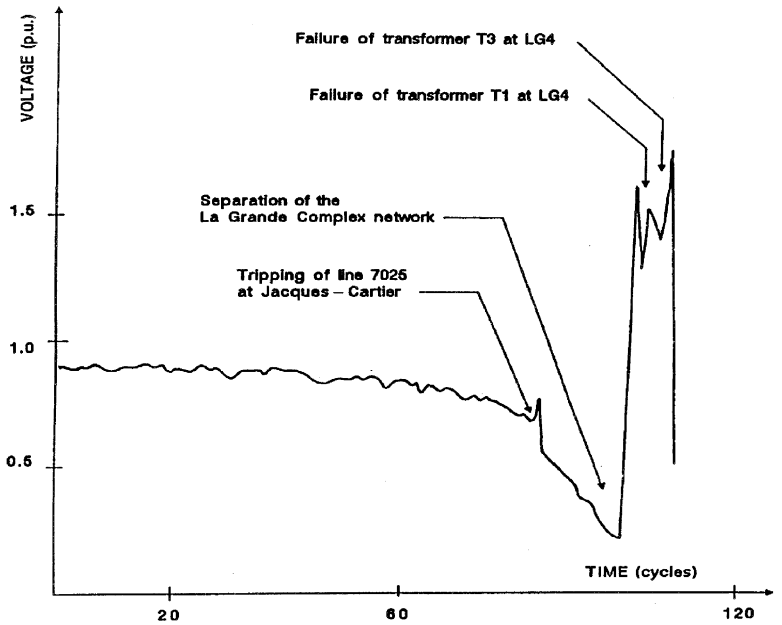


Fig. 4. Voltage profile line 7025 phase A to neutral at Jacques–Cartier substation on James Bay side at 2:45:23.300 EST.

considerably by desensitizing the protections. With these new thresholds (despite the fact that, in addition, they are prevented from tripping after an alarm/warning), the static compensators have been shown, by simulation, to be capable of easily going through the worst storm conditions. Since 1989, the number of static compensators in the western part of the power system (load centers in the La Grande direction) has been increased from nine, of which seven were in operation on March 13, 1989, to a total of 11.

The islanded mode of operation used for the Gentilly nuclear generating station was also reviewed in an aim to avert shutdown during geomagnetic storms.

Subsequent storms in 1991, which caused an interruption on the HVDC links, also led to a number of equipment revisions, including the filters at Radisson substation feed-

Table 2
Damage and unavailability of equipment due to overvoltages that appeared when system separation occurred, based on Hydro-Québec (1989)

Transformer T1, Phase C, at LG-4 (repaired and put back into service on April 26, 1989)
Transformer T3, Phase A, at LG-4
Another phase of T3 at LG-4 when service was restored on March 20, 1989 (due to go back in service on December 15, 1989)
One phase of transformer 3Φ of the static VAR compensator CLC 12 at Chibougamau (transformer replaced by a spare unit on June 1, 1989, due to go back into service in July 1990)
Phase B of reactor XL 2 at Némiskau substation (due to go back into service on September 1, 1989)
Minor damage to the CLCs at Némiskau and Albanel: thyristors and capacitors (repaired in the hours that followed)
Many surge arresters damaged throughout the system: LG-2, LG-4, Némiskau, Bersimis, Montagnais and Churchill Falls

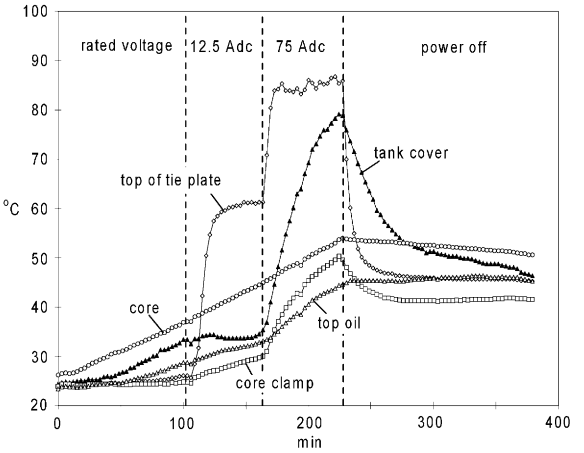


Fig. 5. Measured temperature on 370-MV A transformer rated $735/\sqrt{3}$ kV under DC and AC excitation.

ing the MTDC Radisson–Nicolet–Sandy Pond link (Duncan Electrode Working Group, 1995). It should be noted, too, that the ground return operation of the MTDC link produces ground voltages that bear a resemblance to the effects of geomagnetic storms that affect the transmission system. In an attempt to remedy this problem, Hydro-Québec has developed and installed blocking capacitors on the lines close to the Duncan electrode located near Radisson.

3. Longer-term solutions

Some of the 17 recommendations formulated by a second working group, and all subsequently implemented, are given below:

- Measurement of the telluric potential at a site typical of Hydro-Québec facilities. To this end, Hydro-Québec in collaboration with the Geomagnetic Laboratory set up five measurement sites covering a distance of 250 km in Abitibi, located in the Laurentian Shield. From July 1992 to November 1994, at each one of these five substations, we have measured simultaneously, every 10 s, the three components of the magnetic field, the electric field using 100-m orthogonal dipoles and the relative ground voltage at two points located around a 25 km on each side of the acquisition substations using long telephone line portions. Substation locations were chosen such that the line portions were approximately orthogonal. Measurements have shown 89 10-s events during which the electric field was larger than 1 V/km (max 1.72) at the Louvicourt acquisition substation. Of these events, the most important were eight events on May 9, 1993, 24 on February 21, 1994 and 51 on April 16–17, 1994 (Bolduc et al., 1998, 2000a; Langlois et al., 1996, 2000).

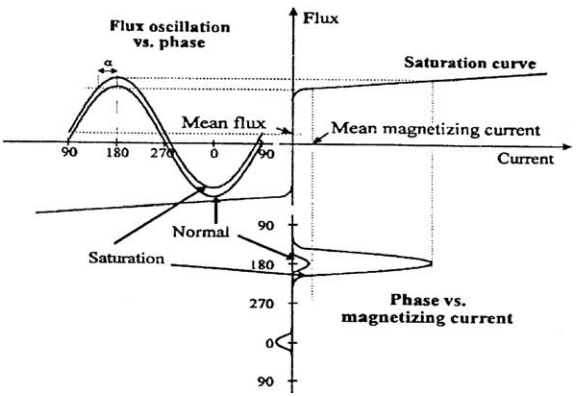
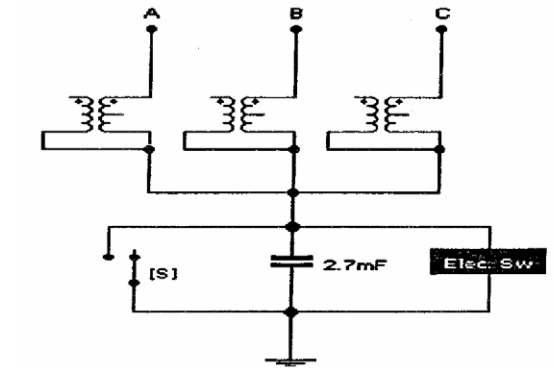


Fig. 6. Magnetizing current vs flux produced by half-cycle saturated single-phase transformer.

- Tolerable DC current in Hydro-Québec's transmission system transformers (Picher et al., 1997). Research and testing (Fig. 5) have shown that the temperature rise in these transformers is located mainly in the tie plates but, although it is quite considerable, it involves little or no risk of damage to the equipment (even if nonmagnetic tie plates would be better). A greater threat is posed by the overvoltages associated with the system resonance resulting from the flow of harmonic currents generated by saturating transformers (Bolduc and Aubin, 1977/78) (Fig. 6).
- Simulation of the currents and voltages induced in the ground by an electrojet, using a finite-element simulation program (Bolduc et al., 1997).
- Upgrading the simulation models in order to speed up the transformer saturation time, which by its very nature is slow, and proposal of a method for measuring the stage of saturation (Bolduc et al., 1990, 2000b; Tousignant



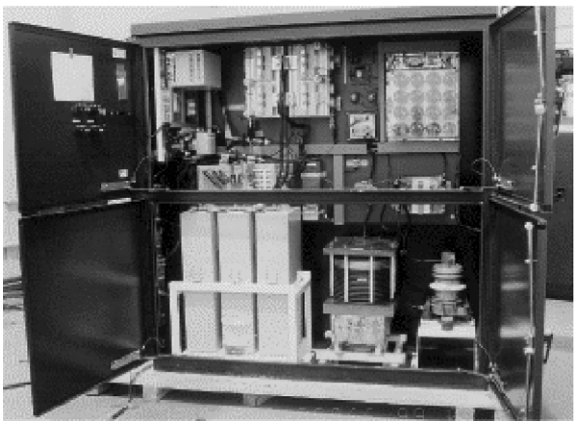


Fig. 7. (a) Basic diagram of the neutral DC blocking device developed at Hydro-Québec; (b) inner view of the prototype (external dimensions: 2000 × 1830 × 610 mm).

et al., 1996; Aubin, 1992; Xu et al., 1994; Lombard et al., 1995).

- Development of a DC current blocking system in the transformer neutrals (Fig. 7) and pilot installation: one such system has been successfully developed and tested at IREQ's laboratories. The pilot installation took place in the spring 2000 and follow-up of its operation and performance will be pursued for 12 months.
- Most of the other studies have shown that the equipment and protection systems in use are adequate following the adjustments made immediately after the power failure.
- Series compensation and the automated shunt reactor operations (MAIS) project are dealt with in another section.

4. March 1991 events

The year 1991 saw many very strong geomagnetic storms. Neither the blocking capacitors nor the series compensators had been installed by then. In March, just as the Hydro-Québec team was ready to carry out impact tests on the main operating system of the MTDC link with DC

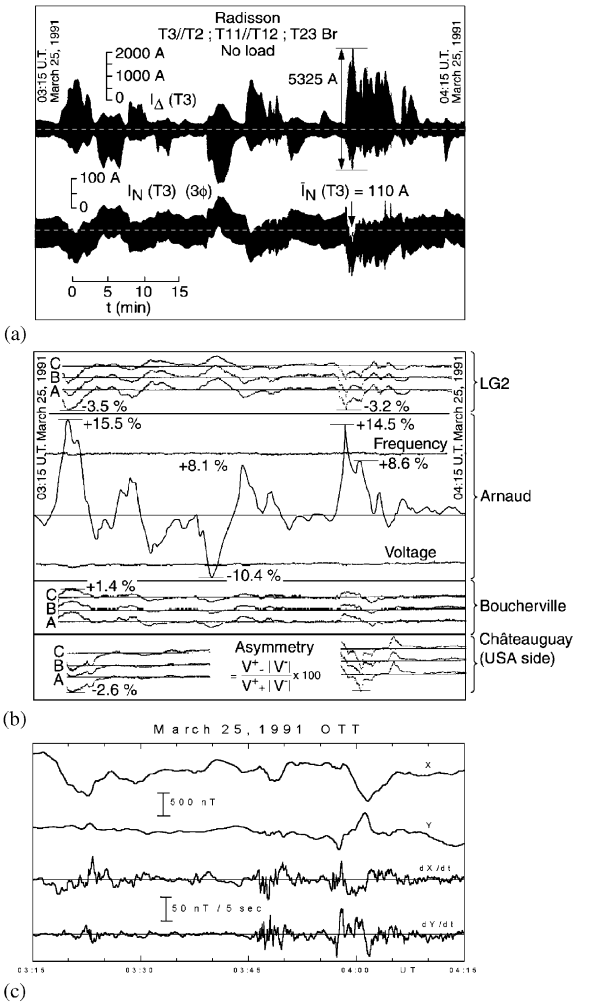


Fig. 8. (a) Tertiary and neutral currents during geomagnetic storm 3:15 to 4:15 UT March 25, 1991; (b) Asymmetries recorded in Hydro-Québec's 735-kV power system during the same period; and (c) Magnetic data at the Ottawa location (Courtesy of GSC).

current ground return up to the Duncan electrode, a major magnetic storm (classified K-8, i.e. not as intense as the storm on March 13, 1989 which was K-9) pounded the earth for 4 days in a row, including March 24, 1991 when it peaked. Since testing was out of the question, the utility took the opportunity to measure and gather data on the impact of storms on the Québec power system. This kind of data had never been collected before. Some figures give a few examples, such as the neutral current and the tertiary current in the neutral of one of the transformers at Radisson substation (two in parallel) (Fig. 8a) for an hour of particularly intense disturbance. It can be seen here that the current exceeds 100 A_{DC} for a few seconds, which implies that more than 200 A_{DC} flowed out of the ground grid in the direction of the lines. Fig. 8b shows the asymmetry measured

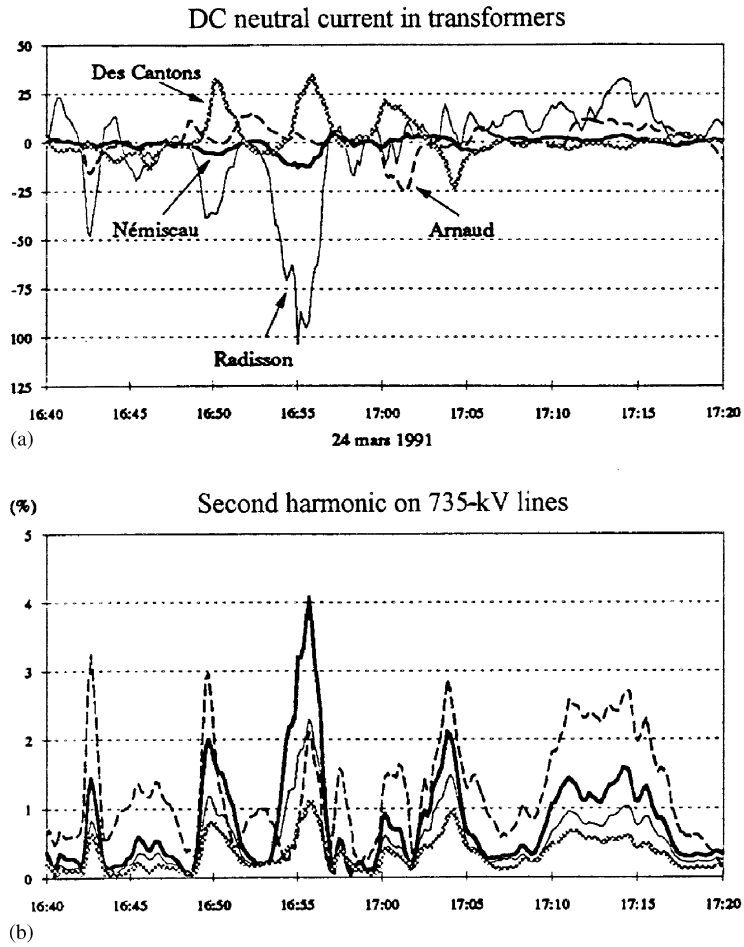


Fig. 9. (a) DC neutral current in transformers; (b) Second harmonic on 735-kV lines at the same locations (UT = local time + 5).

at different points on the system for the same interval and the same scale. We see that it reached 15.5% at Arnaud substation (9.6% was measured at the time the failure occurred in 1989). The geomagnetic recordings on the X-axis obtained by the Geomagnetic Laboratory are also reproduced. Fig. 9 shows the DC current measurements in the neutrals of transformers located in four different substations covering the entire AC system over a 40-min period of the same event. Also seen here are the values of the second harmonics measured in these same substations. Although the currents flowing into the neutral of the Radisson transformer, which is nearer the line end, are far higher than those flowing into Némiskau part way along the line, the even harmonics at the latter substation are almost twice as high because of the additional line impedance there. These harmonics can be seen to decrease at Arnaud as they increase at Némiskau. In addition, the current entering Radisson may be very high, whereas there may be almost no current entering at Arnaud. Currents entering from the north (Radisson or Arnaud) exit via the south (Des Cantons). The same March 24, 2 h later, a current in the order of 85 A_{DC} was measured in the neutral of a transformer at Des Cantons. Aubin (1992) provides other information, including the results of measurements made in Finland on the same day.

During this storm, the directives for operating the system in magnetic storm conditions were applied following an alarm by the voltage asymmetry measuring system. The event tripped three filters of HVDC converter #2 at Châteauguay (00:14, 22:20 and 23:02 EST), one filter at Radisson due to an overcurrent and overprotection which shut down both poles of the converter (15:30 EST), and blocked the firing system for 0.6 s at 00:38 EST on the Madawaska HVDC link. None of the static compensators tripped despite the fact that overcurrent alarms (as predicted) came from compensators at Némiskau and Albanel at 22:20. No damage to equipment was reported, although at 06:33 EST on March 26 a tertiary connection cable in transformer T2 at Radisson proved defective. Was it coinci-

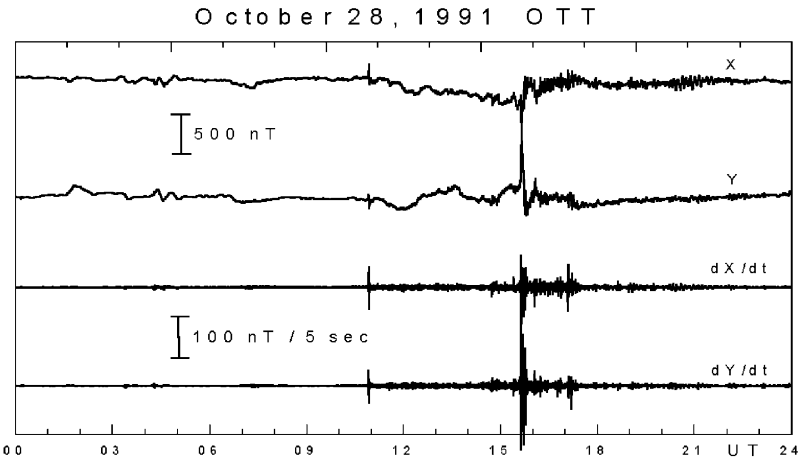


Fig. 10. Ottawa magnetic data during October 28, 1991 event (Courtesy of GSC).

dence or was it the result of extra stress during the previous few days?

The conclusions drawn from this storm were that the filter protection system at Châteauguay and Radisson needed to be overhauled, that the voltage asymmetry measuring system was essential, that the adjustments to the compensators had been effective, and that the power system operating directives for magnetic storm conditions were appropriate and safe and consequently not in need of revision. However, there was room for improvement of the storm detection and warning alarm.

5. October 28, 1991 event

On October 28, 1991 at 10:38 EST, at which time the converter at Radisson was operating in monopolar mode with metallic return and was connected to the main system, a DC current reaching 130–140 A flowed in each of the neutrals of transformers T2 and T3 at that substation. The converter was shut down. By then, the second harmonic of the voltage at Radisson had reached 7% and the asymmetry at Arnaud, 12%. The geomagnetic storm that was taking place did not last long and was relatively harmless, but the very rapid variation in the magnetic field on the Y-axis had a significant impact from the point of view of the ground voltages in the Hydro-Québec system, which tends to run in a north–south direction (Fig. 10). As a result of this event, a filter at Radisson was damaged and had to be modified.

6. Series compensation and the MAIS project

The decision to introduce series compensation on the 735-kV transmission lines from Churchill Falls and the La Grande Complex had already been taken well before 1989 with a view to enhancing the system stability and avoiding general failures in the event of a three-phase fault. The failure that occurred on March 13, 1989 called for a re-examination of that decision. New simulations have shown that implementing series compensation and blocking the passage of DC current wherever compensation is introduced would substantially reduce the generation of harmonics in the system. This in turn would reduce both the load on the static compensators and the amplitude of the resonance. In actual fact, since the series compensation system was completed in 1996 (Fig. 11), asymmetry has never exceeded 3%, except April 7, 2000 UT, when it grew until 7.5% at Châteauguay and 5.5% at Micoua. Nonetheless, it cannot be denied that there has been little significant geomagnetic disturbance since then.

Certain parts of the transmission system such as the entire east–west system of the La Grande Complex, from Brisay to LG-3, via Laforge and LG-4, had not been earmarked for series compensation or the installation of blocking capacitors on the lines. This system was therefore likely to carry DC current and to produce harmonics which could circulate in the main system. Furthermore, it is located in the favorite direction of the electrojets. However, a number of the lines are operated at a lower voltage and have a higher resistance. On the other hand, some transformers are three-phase units, which cause fewer disturbances on the system and generate fewer harmonics in the presence of DC current. Between Lévis–Québec and Grand Brûlé, via Montréal, there is no series compensation either but the soil has far less resistance (less current flowing on the lines) and the density of the facilities reduces the risks.

Implementation of the automated operation of shunt reactors (MAIS) project, with the increase this imposes on the number of shunt reactors in the system, must also be a contributing factor in system stability and help to maintain a better control of the voltage.

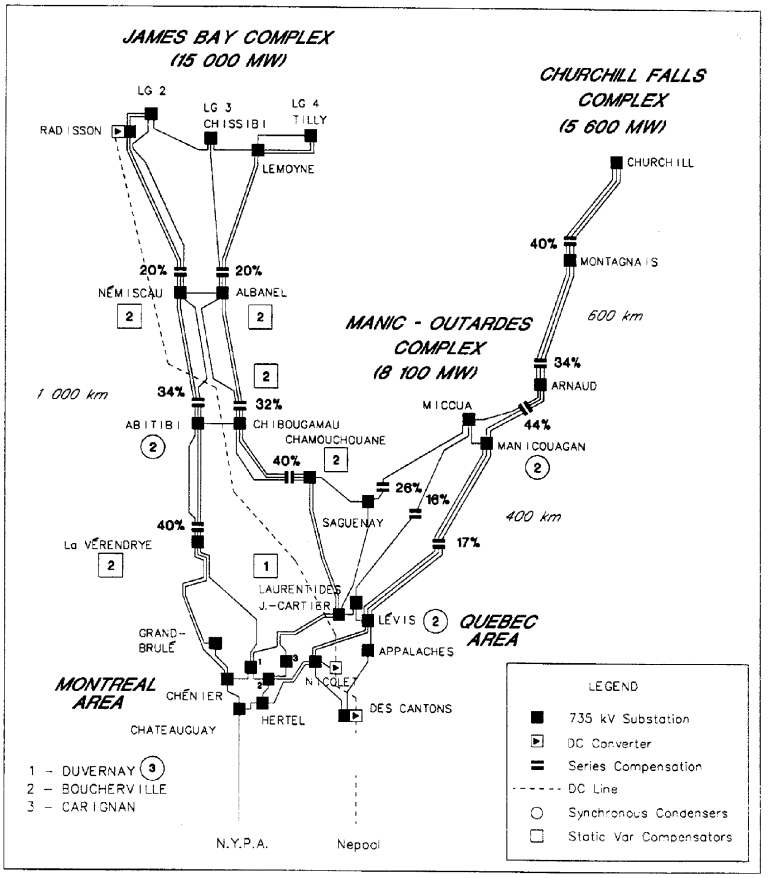


Fig. 11. Hydro-Québec transmission network 1996.

7. Conclusion

This paper has described the influence that geomagnetic storms have had in the past few years on Hydro-Québec's power system and the steps that have been taken to counter or reduce the impact. The studies undertaken to achieve this are outlined.

Hydro-Québec is convinced that the steps taken and the operating modes it uses in the event of such storms are adequate to keep its main grid in proper working order. Among the major modifications and additions, mention should be made of the new adjustments to the static compensators and the implementation of series compensation.

Acknowledgements

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